Advances in Computer Science and Information Technology (ACSIT)
p-ISSN: 2393-9907; e-ISSN: 2393-9915; Volume 11, Issue 1; January-March, 2024, pp. 1-5

http://www.krishisanskriti.org/Publication.html

Application of Phase Change Material for hot Water Production Operated by Photovoltaic Modules-polymer Electrolyte Membrane Fuel Cell

Dr. Kamaljyoti Talukdar

Assistant Professor, Dept. of Mechanical Engineering
Bineswar Brahma Engineering College, Kokrajhar, Assam
E-mail: kamaljyoti.talukdar@gmail.com

Abstract—*Hot water of 100ºC is produced by combination of solar photovoltaic modules of type SW 280, polymer electrolyte membrane(PEM) electrolyzer, PEM fuel cell, and phase change material ($MgCl_2$. $6H_2O$) in Guwahati city, Assam in January and May. Sunlight falling on photovoltaic modules(SW 280) during day time generates current and is sent to inverter through charge controller. From inverter some amount of current is extracted for heating solid form of phase change material ($MgCl_2$. $6H_2O$) in salt storage tank to liquid form at a rate of 10.0114 kg/s after passing through 50 ohm resistance. The remaining amount of current from the inverter is sent to pump for pumping 10 kg/s of water at ambient temperature to 100ºC through salt storage tank by utilizing sensible and latent heat of fusion of phase change material. After meeting the current requirements for salt storage tank and pump, extra current unused is passed to PEM electrolyzer where water present in electrolyzer is dissociated into hydrogen and stored in gas compressor. During night time hydrogen from gas compressor is utilized by PEM fuel cell for producing required current to salt storage tank and pump. The power requirements for salt storage tank and pump are obtained from 68 solar photovoltaic modules in parallel, 2 in series of model SW 280 assisted by 17.627kW electrolyzer and nine 382.368W PEM fuel cell stack. The power required by gas compressor for compressing hydrogen for storage produced by 17.627kW electrolyzer is obtained from 5 solar photovoltaic modules in parallel, 2 in series of model SW 280.*

Keywords: *Electrolyzer, Phase change material, Polymer electrolyte membrane, Solar photovoltaic.*

INTRODUCTION

Hot water is needed in day to day life for essential purposes. Hot water can be produced by heating water by burning fossil fuels, by solar concentrators, solar photovoltaic heating etc. The present paper deals with heating water by combination of solar photovoltaic modules, phase change material ($MgCl_2$. $6H_2O$) and PEM(polymer electrolyte membrane) electrolyzer, fuel cell. Some authors have used different fuel cells for water heating. In [1] authors used solid oxide fuel cell (SOFC) based micro combined heat and power (micro-CHP) systems for residential space and water heating demands in the UK for morning and evening periods. In [2] authors used a thermoelectric heater for enhancing the fuel cell micro combined heat and power system's water heating capacity. In [3] authors considered a 5kW PEM fuel cell including burner, steam reformer, and water heater for domestic application. In [4] authors performed a demonstration in a small apartment building in Osaka City for obtaining electricity, hot water, and hydrogen based on fuel cells and energy networks. In [5] authors implemented a regional hydrogen energy interchange network among energy consumers for the interchange of energy comprising hydrogen, electricity, and heat (hot water) in residential areas. In [6] authors designed, performed and analyzed fuel cell based residential combined heat and power (CHP) system i.e. hot water and space heating requirements where fuel cell was operated on natural gas.

In present paper hot water is obtained from combination of solar photovoltaic modules, PEM electrolyzer, PEM fuel cell and phase change material ($MgCl_2$. $6H_2O$) for climatic condition of Guwahati city in Assam.

SYSTEM LAYOUT

Figure 1 shows a layout of proposed water heating system by combined solar photovoltaic modules, PEM electrolyzer, PEM fuel cell and phase change material($MgCl_2$. $6H_2O$). During day time solar radiation falling on solar photovoltaic modules generates current I_{PV}. From charge controller the current required for sensible heating and melting the salt ($MgCl_2$. $6H_2O$) as phase change material (I_{pcm}) is sent to salt storage tank after passing through an inverter and 50 ohm resistance. Also current (I_{pump}) required for pumping m_{water} (10 kg/s) water by centrifugal pump from a datum height of 5m through salt storage tank for heating water from ambient T_a(ºC) (25º C) to 100ºC is sent to pump through an inverter.

After meeting the current requirement for salt storage tank (I_{pcm}) and pump (I_{pump}), extra current i.e. (I_{PV}- (I_{pcm}+I_{pump})) is sent to PEM electrolyzer where in electrolyzer (I_{PV}-(I_{pcm}+I_{pump})) current is used for dissociating water present in electrolyzer to hydrogen and oxygen. Hydrogen produced in electrolyzer is stored in gas storage cylinder. Hydrogen has large volume; hence it requires large storage volume. Hence hydrogen is compressed and stored in a compressed form in a tank where current required for pressurization of hydrogen (I_G) is obtained from solar photovoltaic modules shown in figure 1. During night time, current required for heating salt storage tank and powering centrifugal pump i.e. ((I_{pcm}+I_{pump})-I_{PV}) comes from PEM fuel cells where fuel cells obtain hydrogen from hydrogen storage tank.

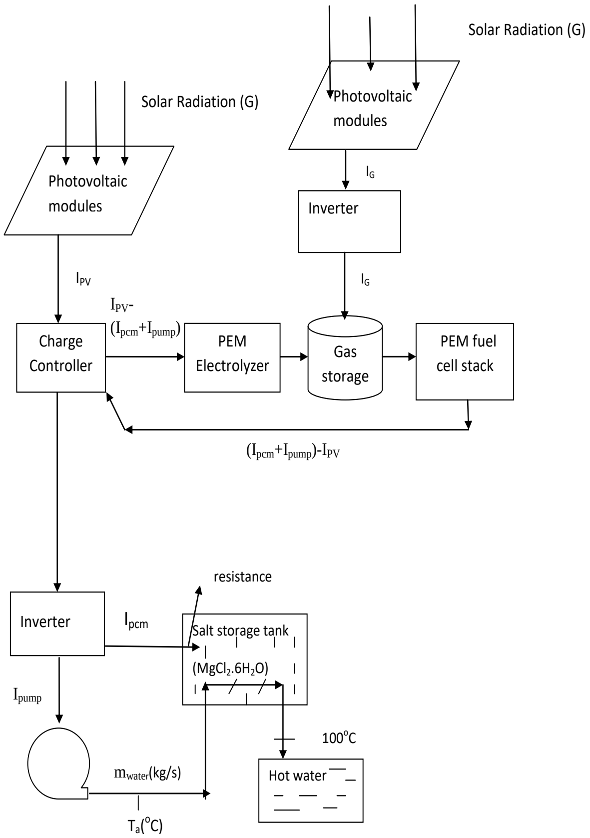

Figure 1: Schematic view of combined solar photovoltaic modules, PEM electrolyzer, PEM fuel cell and phase change material for hot water production of 100ºC

MODELING OF COMBINED SYSTEMS

The amount of heat needed in kW to raise m_{water}(kg/s) of water from ambient $T_{a,w}$(ºC) (25º C) to 100ºC is given by equation 1.

$$Q_{water} = m_{water} \times C_p \times (100 - T_{a,w}) \quad (1)$$

Where, m_{water}-mass flow rate of water (10kg/s), C_p- specific heat of water(4.2 kJ/kg.K), 100- temperature of hot water produced in ºC, $T_{a,w}$-ambient temperature of water in ºC.

The heat required by water (Q_{water}) is supplied by sensible heating and latent heat of fusion of $MgCl_2$. $6H_2O$(Q_{salt}) present in salt storage tank.

$$Q_{water} = Q_{salt} = (m_{salt} \times C_{p,salt} \times (115 - T_{a,salt})) + (m_{salt} \times 165) \quad (2)$$

Where, m_{salt}- mass of salt required for supplying Q_{water} heat, $C_{p,salt}$- specific heat of solid salt(1.72 kJ/kg. ºC)[7], 115- melting point temperature of $MgCl_2$. $6H_2O$ in ºC[7], $T_{a,salt}$- 28ºC(say) 165- latent heat of fusion of $MgCl_2$. $6H_2O$ salt in kJ/kg[7].

The amount of current required by salt storage tank (I_{pcm}) from photovoltaic modules after passing through resistance of 50 ohm is given by:

$$I_{pcm} = \sqrt{\frac{Q_{salt}}{resistance}} \quad (3)$$

Where, resistance is 50 ohm.

Power required by pump to pump water through salt storage tank for heating purpose is given by:

$$W_p = (m_{water} \times 5 \times 9.81) / 0.9 \quad (4)$$

Where, m_{water}-mass flow rate of water (10kg/s), 5- piezometric height of pump in metre, 9.81- acceleration due to gravity in m/s^2, 0.9- centrifugal pump efficiency[8]

The detailed calculations of solar photovoltaic modules along with module specifications are available in [9] and [10] respectively. From [11], [12], [13] solar radiation, wind speed data and ambient temperature for January and May in Guwahati city are obtained.

Series number of photovoltaic modules (N_s) is given by:

$$N_s = \frac{48}{V_{\mathrm{mod}}} \quad (5)$$

Where, 48- voltage of the system and V_{mod}-module's maximum voltage[10].

Current requirement from photovoltaic modules(I_{spv}) is given by:

$$I_{spv} = \left(\frac{I_{pcm} \times 1.25}{0.85 \times \eta_{inverter} \times 7 \times \eta_{chargecontroller}}\right) + \left(\frac{W_p \times 1.25}{48 \times 0.85 \times \eta_{inverter} \times 7 \times \eta_{chargecontroller}}\right) \quad (6)$$

Where, 1.25-derating factor of photovoltaic module[14], 48- voltage of the system, 0.85-power factor, 0.85- efficiency of inverter($\eta_{inverter}$),7- Guwahati's mean sunshine hours in [15], 0.85-efficiency of charge controller($\eta_{chargecontroller}$).

Parallel number of photovoltaic modules(N_p) is given by:

$$N_p = \frac{I_{spv}}{I_{\mathrm{mod}}} \quad (7)$$

Where, I_{mod}- module's maximum current [10].

In electrolyzer water present in it is dissociated into hydrogen and oxygen gas by utilizing excess current after meeting for salt storage tank and centrifugal pump. For dissociating water by electrolyzer a number of electrolyzer cells are used in series.

The amount of hydrogen produced (in gm mol) with series of electrolyzer cells is given by[16]:

$$M_{electrolyzer} = \frac{(I_{PV} - I_{SPV}) \times N_{electrolyzer} \times \eta_{electrolyzer} \times 3600}{2F} \quad (8)$$

Where, (I_{PV}-I_{SPV})-excess current obtained after meeting salt storage tank and centrifugal pump, $N_{electrolyzer}$-number of electrolyzer cells in series, $\eta_{electrolyzer}$ -electrolyzer electrical efficiency[16], F-96500 C/mol.

The output voltage of a PEM fuel cell($V_{fuelcell}$) is given by[16]:

$$V_{fuelcell} = V_{Nerst,\,fuelcell} - V_{activation,\,fuelcell} - V_{ohmic,\,fuelcell} - V_{concentration,\,fuelcell} \quad (9)$$

Where, $V_{Nerst,fuelcell}$- Nerst potential of PEM fuel cell, $V_{activation,\ fuel\ cell}$- activation voltage required for occurring of chemical reaction, $V_{ohmic,fuelcell}$-voltage generated due to resistance to the flow of current, $V_{concentration,fuelcell}$-voltage generated due to deficient supply of reactant at electrodes.

The above mentioned different potentials in equation(9) are obtained from [16].

The number of fuel cells connected in series forming a stack ($N_{fuelcell,series}$) is given by[16]:

$$N_{fuelcell,,series} = \frac{V_{system}}{V_{fuelcell}} \quad (10)$$

Number of fuel cell stacks needed in parallel ($N_{fuelcell,parallel}$) is given by [16]:

$$N_{fuelcell,\,parallel} = \frac{(I_{SPV} - I_{PV})}{I_{cell}} \quad (11)$$

Where, (I_{SPV}-I_{PV})- current requirement during night time, I_{cell}-current generated by single fuel cell.

The hydrogen consumed by a fuel cell stack ($M_{fuelcell}$) is given by [16]:

$$M_{fuelcell} = \frac{(I_{SPV} - I_{PV}) \times N_{fuelcell,series} \times 3600}{F \times \eta_{fuel,utilization}} \quad (12)$$

Where, $\eta_{fuel,utilization}$ -fuel cell utilization factor (0.9)[16]

In gas compressor hydrogen produced in electrolyzer is compressed and stored in a hydrogen gas storage tank due to the fact that hydrogen having low density will require large volume for storage. Hence by using gas compressor hydrogen can be stored in small tank. The gas compressor derives its energy from extra solar photovoltaic modules shown in figure 1.

The power required for running the gas compressor ($W_{gas,c}$) is given by[16]:

$$W_{gas,c} = \frac{M_{H_2} \times C_{p,hydrogen} \times T_{inlet}}{\eta_{g,compressor}} \times \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (13)$$

Where, M_{H2}-mass flow rate of hydrogen(kg/s), $C_{p,hydrogen}$-specific heat of hydrogen at constant pressure (14.304 kJ/kg.K), T_{inlet}- inlet temperature of hydrogen to gas compressor, $\eta_{g,compressor}$ -efficiency of gas compressor, P_2-exit pressure of hydrogen from gas compressor, P_1- inlet pressure of hydrogen to gas compressor(atmospheric pressure), γ -ratio of specific heats of hydrogen.

The current requirement for running gas compressor is obtained from separate photovoltaic module shown in figure with inverter.

$$I_{SPV,G} = \frac{W_{gas,c} \times 1.25}{48 \times 0.85 \times 7 \times 0.85} \quad (14)$$

Where, $W_{gas,c}$-total compressor work(in W) in a day, 1.25-derating factor[14], 48-system voltage, 0.85-power factor, 0.85-inverter efficiency,7-average sunshine hours in Guwahati[15].

RESULTS AND DISCUSSIONS

From equation 1, to heat 10 kg/s of water from 25^{o}C to 100^{o}C, 3150 kW of heat is required.

Similarly from equation 2, amount of salt required for transferring sensible and latent heat of fusion of salt to heat 10 kg/s of water is found to be 10.0114kg/s. The volume of salt storage tank is considered to be 0.00641 m^3.

From equation 3, current required for transferring sensible heat from 28^{o}C to 115^{o}C and latent heat of fusion of salt for heating water is found to be 250.998 A after passing through 50 ohm resistance.

From equation 4, pumping work required for pumping 10 kg/s of water through salt storage tank is found to be 545 W.

If the velocity of flow of water is considered 0.1 m/s, then required diameter and length of pipe for effective heat transfer to water from salt storage tank is considered as 5cm and 63.694 cm respectively.

The above values from equation 1 to 4 are found to be constant throughout the day.

Table 1 shows the hydrogen consumption and hydrogen generation (in gmole/hour) for January. During non sunshine hours i.e. 12:30 AM, 3:30 AM, 5:30 AM and 8:30 PM hydrogen consumption (in gmole/hour) remains constant as current required by salt storage tank and centrifugal pump is same. At 5:30 PM some amount of hydrogen is consumed although sunshine is present. From 8:30 AM to 11:30 AM hydrogen generation (in gmole/hour)increases and again decreases to 2:30 PM. This is due to the fact that solar radiation increases from 8:30AM to 11:30AM and decreases from 2:30 PM to 5:30 PM. As a result availability of excess current after meeting salt storage tank and centrifugal pump from photovoltaic modules for producing hydrogen by PEM electrolyzer increases from 8:30AM to 11:30AM and decreases to 2:30 PM.

Table 1: Hydrogen consumption and generation in January

Time in hours	Hydrogen consumption(gmol)	Hydrogen generated(gmol)
12:30 AM	147.509	0.0
3:30 AM	147.509	0.0
5:30 AM	147.509	0.0
8:30AM	0.0	126.183
11:30AM	0.0	296.221
2:30PM	0.0	208.025
5:30PM	38.932	0.0
8:30PM	147.509	0.0

Table 2 shows the hydrogen consumption and hydrogen generation (in gmole/hour) for May. During non sunshine hours i.e. 12:30 AM, 3:30 AM, 5:30 AM and 8:30 PM hydrogen consumption (in gmole/hour) remains constant as current required by salt storage tank and centrifugal pump is same. At 5:30 PM some amount of hydrogen is consumed although sunshine is present. From 8:30 AM to 11:30 AM hydrogen generation (in gmole/hour) increases and again decreases to 2:30 PM. This is due to the fact that solar radiation increases from 8:30AM to 11:30AM and decreases from 2:30 PM to 5:30 PM. As a result availability of excess current after meeting salt storage tank and centrifugal pump from photovoltaic modules for producing hydrogen by PEM electrolyzer increases from 8:30AM to 11:30AM and decreases to 2:30 PM.

Table 2: Hydrogen consumption and generation in May

Time in hours	Hydrogen consumption(gmol)	Hydrogen generated(gmol)
12:30 AM	147.509	0.0
3:30 AM	147.509	0.0
5:30 AM	147.509	0.0
8:30AM	0.0	182.578
11:30AM	0.0	399.053
2:30PM	0.0	286.680
5:30PM	9.161	0.0
8:30PM	147.509	0.0

It is seen that hydrogen consumption is more at 5:30 PM in January than May. It is due to greater solar radiation in May resulting in greater hydrogen production in May leading to less amount of hydrogen consumption in May.

The cumulative amount of hydrogen produced/stored and hydrogen consumption in January and May are 630.429 gmol, 628.968 gmol; and 868.311 gmol, 599.197 gmol respectively.

It is seen that hydrogen generation (in gmole/hour) in May is more than January due to the fact that solar radiation in May is more than January. Hence more amount of current is produced by photovoltaic modules resulting in greater hydrogen production by PEM electrolyzer in May. Hydrogen consumption is more in January than May due to greater hydrogen consumption at 5:30 PM in January than May.

The requirements of different components and parameters used are illustrated in table 3.

Table 3: Input parameters and ratings of different power system components

Components	Parameters/Components	Value/Ratings
Solar photovoltaic system	No. of photovoltaic modules in parallel	68
	No. of photovoltaic modules in series	2
	No. of photovoltaic modules in parallel for gas compressor	5
	No. of photovoltaic modules in series for gas compressor	2
Electrolyzer	No. of cells in series($N_{electrolyzer}$)	90
	Cell area	86.4 cm^2 [16]
	Maximum current density	1.6 A/cm^2 [16]
	Membrane's dry thickness	178 micron[16]
	Electrolyzer input at 48 V	17.627 kW
Fuel cell	Exchange current density	10^{-4} A/cm^2
	Charge transfer coefficient of reaction	0.5 [16]
	Cell effective area	100 cm^2 [16]
	Operating current density	0.1 A/cm^2 [16]
	Number of fuel cell in one stack/series($N_{fc,series}$)	47
	Number of fuel cell stacks/parallel($N_{fc,parallel}$)	9
	Maximum output of each fuel cell stack	7.966 A, 382.368W
Hydrogen compressor	Isentropic efficiency	0.7 [16]
	Specific heat of hydrogen at constant pressure	14.304 kJ/kg.K [16]
	Inlet pressure	1.01325 bar
	Exit pressure	200 bar [16]
	Gas compressor rating at 48 V	3.98 kW

CONCLUSIONS

Based on the analysis it can be concluded that for producing 10 kg/s of hot water, a total of 68 photovoltaic modules in parallel, 2 in series(for powering salt storage tank, centrifugal pump with PEM electrolyzer) and 5 photovoltaic modules in parallel, 1 in series(for gas compressor) along with 17.627 kW electrolyzer and nine 382.368W PEM fuel cell stack are sufficient to run the whole system.

The study is done in January and May because January and May have the minimum solar radiation, temperature and maximum solar radiation and temperature respectively, so if the system works well in the minimum and maximum conditions, the system will work well throughout the year.

REFERENCES

[1]Hawkes, A.D., Aguiar, P., Croxford, B., Leach, M.A., Adjiman, C.S., Brandon, N.P., "Solid oxide fuel cell micro combined heat and power system operating strategy: Options for provision of residential space and water heating", *Journal of Power Sources*, 164, 1, January 10 2007, pp.260-271.

[2] Shen, Y., Zhao, B., Kwan, T.H., Yao, Q., "Numerical analysis of combined air-cooled fuel cell waste heat and thermoelectric heating method for enhanced water heating", *Energy Conversion and Management*, 213, June 1 2020, pp. 112840.

[3]Saidi, M.H., Abbassi, A., Ehyaei, M.A., "Exergetic Optimization of a PEM Fuel Cell for Domestic Hot Water Heater", *J. Fuel Cell Sci. Technol.*, 2,4, November 2005, pp.284-289.

[4]Aki, H.,Taniguchi, Y., Tamura, I., Kegasa, A., Hayakawa, H., Ishikawa, Y., Yamamoto, S., Sugimoto, S., "Fuel cells and energy networks of electricity, heat, and hydrogen: A demonstration in hydrogen-fueled apartments", *International Journal of Hydrogen Energy*, 37,2, January 2012, pp. 1204-1213.

[5]Aki, H., Yamamoto, S., Kondoh, J., Maeda, T., Yamaguchi, H., Murata, A., Ishii, I., "Fuel cells and energy networks of electricity, heat, and hydrogen in residential areas", *International Journal of Hydrogen Energy*, 31, 8, July 2006, pp. 967-980.

[6]Ahmed, S.,Papadias, D. D., Ahluwalia, R. K., "Configuring a fuel cell based residential combined heat and power system", *Journal of Power Sources*, 242, November 15 2013, pp. 884-894.

[7]Tiwari, G. N., *Solar energy-Fundamentals, Design, Modeling and Applications*, Narosa Publishing House, 2004.

[8] Pump Efficiency—What Is Efficiency? - Pumps & Systems, https://www.pumpsandsystems.com/pump-efficiency-what-efficiency.

[9]Chenni, R., Makhlouf, M., Kerbache, T., Bouzid, A., "A detailed modeling method for photovoltaic cells", *Energy*, 32, 2007, pp.1724-1730.

[10]How do I read the solar panel specifications?-altEStore https://www.altestore.com/blog/2016/04/how-do-i-read-specifications-of-my-solar-panel/#.YhOABOhBzIU.

[11]Solar Irradiance - calculate the solar energy available on your ..., http://www.solarelectricityhandbook.com/solar-irradiance.html.

[12]Solar Energy Assessment Report,For 100kWp at Guwahati, Assam,India by ezysolare

[13]Weather History & Data Archive | Weather Underground, https://www.wunderground.com/history.

[14]Telecommunication Engineering Centre (TEC), New Delhi, Planning and maintenance guidelines for SPV power, http://www.tec.gov.in/guidelines.html.

[15]Annual Sunshine in India - Current Results, http://www.currentresults.com/Weather/India/annual-sunshine.php

[16]Ganguly, A., Misra, D., Ghosh, S. "Modeling and analysis of solar photovoltaic-electrolyzer-fuel cell hybrid power system integrated with a floriculture greenhouse",*Energy and Buildings*, 42, 2010, pp.2036-2043.